applied sciences

Systematic Review

Cementitious Grouts in Ground Support Systems: A PRISMA-Guided Bibliometric and Mechanistic Review

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Abstract

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, combining bibliometric mapping and mechanistic synthesis to provide a unified evidence-based review of cementitious grouts in ground support systems. The bibliometric layer quantifies global research activity, while the systematic synthesis interprets how material composition, pozzolanic chemistry, and rheology control grout performance and sustainability. This study presents a systematic review complemented by bibliometric analysis to synthesise global research trends and technical advances in grout design. A dataset of 1200 articles was screened, from which 101 journal papers met the inclusion and quality criteria and were analysed in detail. Co-occurrence mapping of author keywords was then used to identify research hotspots and collaborative structures. The bibliometric analysis revealed that Construction and Building Materials is the leading outlet. Co-authorship mapping highlighted strong international collaboration, with leading clusters centred on supplementary cementitious materials, rheology, and microstructural analysis. The technical review consolidates five interrelated themes: reinforcement mechanisms, cementitious grouts, chemical reactions and pozzolanic reactivity, fresh and hardened state properties, and microstructural development with rheological behaviour. Across these themes, supplementary cementitious materials and waste-derived binders have emerged as central to both performance enhancement and carbon reduction, while advanced experimental and modelling techniques have refined understanding of microstructural evolution and grout–rock–bolt interactions. Collectively, the findings underline that cementitious grouts are no longer passive fillers but engineered composites designed for mechanical efficiency, durability, and environmental responsibility. Key research gaps remain in the standardisation of rheological testing, long-term durability under complex field conditions, and integration of life-cycle assessment into grout development. Addressing these challenges will be critical for the design of next-generation grouts capable of meeting the dual imperatives of safety and sustainability in mining and civil engineering.

Keywords: cementitious grouts; ground reinforcement; rheology; systematic review; bibliometric analysis

Academic Editors: Daniele Gaetano and Lorenzo Leonetti

Received: 15 October 2025
Revised: 21 November 2025
Accepted: 21 November 2025
Published: 24 November 2025

Citation: Entezam, A.; Nourizadeh, H.; Burey, P.; McDougall, K.; Craig, P.; Jodeiri Shokri, B.; Entezam, S.; Aziz, N.; Mirzaghorbanali, A. Cementitious Grouts in Ground Support Systems: A PRISMA-Guided Bibliometric and Mechanistic Review. *Appl. Sci.* **2025**, *15*, 12439. https://doi.org/10.3390/app152312439

1. Introduction

The stability of underground excavations relies fundamentally on effective ground support systems, which prevent rock detachment and maintain the integrity of openings under static and dynamic loads. Among these systems, fully grouted rock bolts/cable bolts (FGRB/FGCBs) have become the most widely applied reinforcement technology in both mining and civil engineering due to their ability to mobilise the self-supporting capacity of the rock mass while providing corrosion protection and long-term stability [1,2]. At the core of this technology lies the grout medium, which is a mechanical coupling between the reinforcement element and the surrounding rock, mediating load transfer via its shear resistance across the bolt–grout and grout–rock interfaces [3–5].

Conventional cementitious grouts, typically based on ordinary Portland cement (OPC), have been the backbone of encapsulation systems for decades. Their extensive use stems from well-established production, low cost, and reliable performance under standard conditions. Yet, OPC production is energy-intensive, accounting for 7–8% of global anthropogenic CO_2 emissions [6]. In ground support operations, where large grout volumes are consumed, this environmental burden is particularly problematic. Furthermore, OPC-based grouts face durability challenges in aggressive underground environments, such as high sulphate groundwater, acidic mine drainage, or elevated stress regimes, where microcracking, leaching, and reduced long-term stiffness may compromise support effectiveness [7].

To address these limitations, recent research has shifted toward the incorporation of supplementary cementitious materials (SCMs) and alternative binders. Fly ash, silica fume, metakaolin, and ground granulated blast-furnace slag (GGBS) have been widely studied for their ability to partially replace clinker, refine hydration kinetics, and densify the microstructure of hardened grout [8]. Waste-derived binders, including rice husk ash, municipal solid waste incineration ash, and steel slags, are increasingly investigated to improve both performance and sustainability [9]. Parallel developments have concentrated on the rheological optimisation of cementitious grouts, which is critical for ensuring proper encapsulation of reinforcement elements. Fresh-state properties such as yield stress, plastic viscosity, and thixotropy determine whether the grout can be pumped, injected, and retained in boreholes without segregation or bleeding. Rheological studies have shown that SCMs such as nanosilica or finely ground slag can significantly alter these parameters, influencing stability and injectability [10,11]. Beyond material modifications, advanced rheometry is increasingly employed to characterise structural build-up during rest, shear thinning under pumping, and setting-related changes that mirror early microstructural evolution [12].

Microstructural investigations using advanced techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and nanoindentation have further clarified how chemical reactions and pozzolanic activity shape the interfacial transition zones between grout, bolt element, and rock mass, which ultimately control the shear transfer mechanism and bond strength capacity [13]. In grout–rock–bolt systems, interfacial transition zone (ITZ) characteristics are particularly important: weak or porous ITZs may act as slip planes, whereas dense ITZs enhance shear transfer and anchorage performance [14]. While the present review focuses specifically on cementitious grouts, broader research on aluminosilicate activation and clay mineralogy, such as recent studies on geopolymer-stabilised clays exploring the influence of CaO/Al_2O_3 and SiO_2/Al_2O_3 ratios as well as mineralogical effects on strength development, helps contextualise the chemical and microstructural mechanisms that motivate several of the themes discussed in this work [15,16].

Alongside these scientific advances, sustainability considerations are increasingly steering grout research. The valorisation of industrial by-products and agricultural wastes as cement replacements reflects a global shift toward resource efficiency and reduced emissions. Life-cycle assessments of blended binders demonstrate significant potential for reducing embodied carbon while maintaining or improving performance in underground reinforcement applications [17]. These innovations are particularly relevant to the mining industry, where grouting represents a critical intersection of safety, operational efficiency, and environmental responsibility.

Despite these advances, the literature remains fragmented across multiple domains, including materials science, geomechanics, rheology, and sustainability, each advancing along separate trajectories. The absence of integrated synthesis has made it difficult to track the evolution of research priorities and identify cross-cutting opportunities. To overcome this fragmentation, the present work adopts a PRISMA-guided systematic review framework that integrates both bibliometric mapping and mechanistic synthesis. Bibliometric mapping tools such as VOSviewer and CitNetExplorer enable the quantification of co-authorship networks, keyword co-occurrence, and citation structures, thereby providing the quantitative overview required by PRISMA for transparency and replicability [18,19]. Building upon this, the mechanistic synthesis interprets how material composition, pozzolanic chemistry, and rheological behaviour influence the structural performance and environmental sustainability of cementitious grouts in reinforcement systems.

The present study responds to this need by conducting a systematic and bibliometric review of cementitious grouts in ground support applications. A dataset of 1200 publications was assembled and analysed, with keyword co-occurrence mapping used to distil research into five clusters: reinforcement mechanisms, cementitious grouts, chemical reactions and pozzolanic reactivity, fresh and hardened state properties, and microstructural development with rheological behaviour. Each cluster is critically examined to evaluate how innovations in material composition, processing, and characterisation techniques are reshaping the performance and sustainability of grout systems. By integrating bibliometric mapping with an in-depth review of experimental and modelling studies, this work provides the first comprehensive synthesis of grout research at the intersection of geomechanics, material science, and sustainability. The objectives of the review are threefold: (i) to chart the intellectual landscape of grout-related research and identify leading journals, institutions, and authors; (ii) to consolidate knowledge on the material, chemical, and mechanical behaviour of cementitious grouts in reinforcement systems; and (iii) to define future research pathways that align technical innovation with the imperatives of durability and environmental responsibility. To meet the second and third objectives, the Discussion synthesises current mechanistic evidence on material, chemical, and rheological behaviour and interprets its implications for durability, field-scale performance, and sustainable grout development. This integrated PRISMA-based structure ensures that bibliometric evidence supports, rather than competes with, the mechanistic interpretation, thus maintaining a clear and focused review framework.

The originality of this review lies in three main aspects. First, it provides a PRISMA-guided bibliometric map focused specifically on cementitious grouts in ground support systems, rather than on cementitious materials or rock reinforcement in general. Second, it integrates this mapping with a mechanistic synthesis that links grout composition, pozzolanic chemistry, rheological behaviour, microstructure, and load transfer in grout–rock–bolt systems. Third, it identifies and discusses critical knowledge gaps related to rheological test standardisation, time-dependent degradation under complex underground boundary conditions, and the limited integration of durability and life-cycle assessment in grout design. Together, these elements clarify the specific research gaps explored in this study and position the review as a bridge between materials science, geomechanics, and sustainability.

2. Research Methodology

This study follows a five-stage process to identify, map, and interpret the literature on the mechanical and rheological behaviour of cementitious grouts. Figure 1 outlines the end-to-end pathway from the initial Scopus query to thematic synthesis.

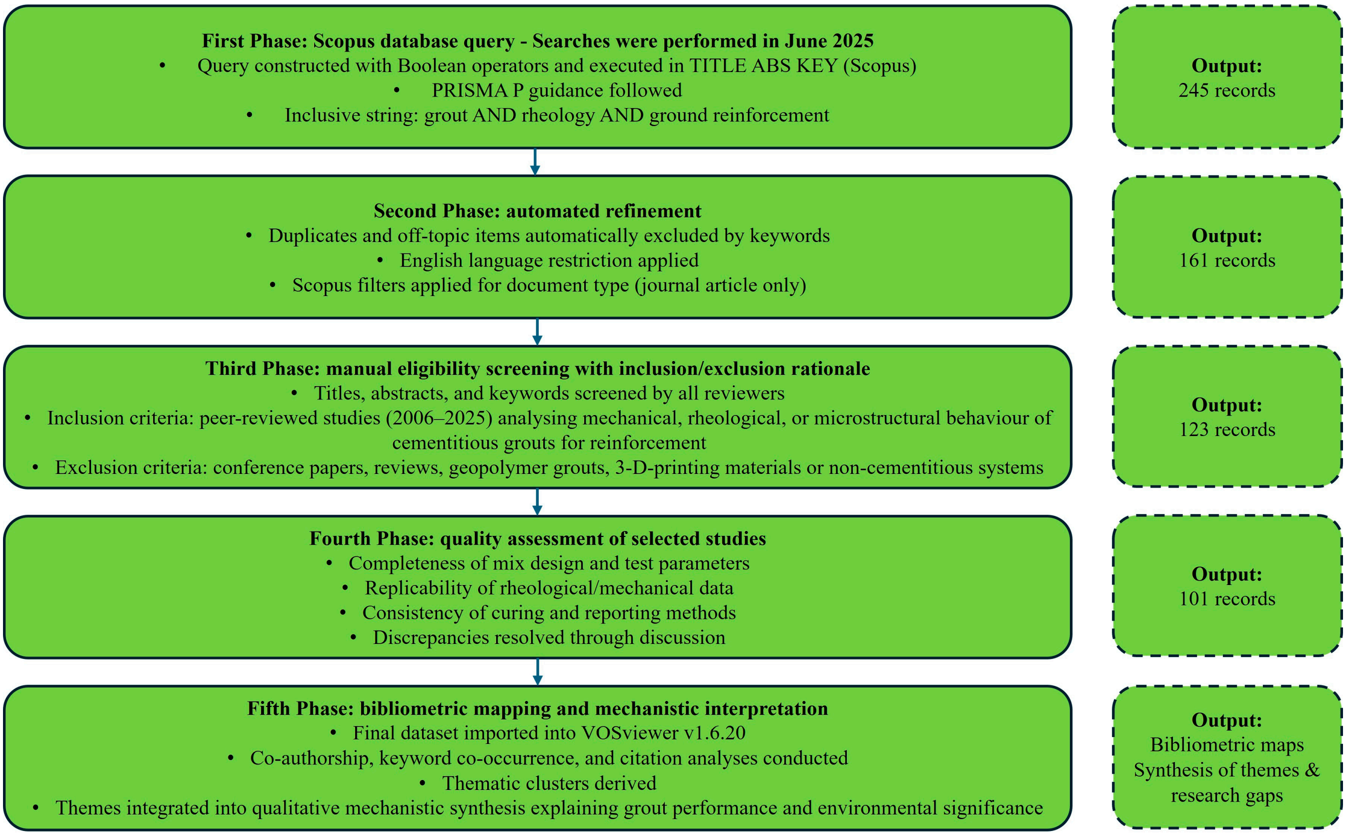

Figure 1. PRISMA-compliant workflow for database search, screening, and synthesis.

(1) Targeted database query (Scopus)

Boolean search strings are built around grout-specific terms (e.g., grout, rheology, etc.), coupled with cementitious modifiers and common test methods. The aim is broad coverage without losing topical focus.

(2) Eligibility Criteria

Titles, abstracts, and keywords were screened against the following inclusion/exclusion rules:

- Inclusion: English-language journal articles (2006–2025) presenting primary data or validated modelling on cementitious-grout rheology, mechanics, or microstructure in ground-reinforcement applications.
- Exclusion: Conference papers, reviews, editorials, or studies focusing on polymeric, geopolymeric, or 3D-printing binders, as well as non-grout concretes or asphaltic materials. No automation tools were used beyond Scopus filters.

(3) Quality Assessment

Each study was independently assessed by all reviewers for methodological quality, considering (i) completeness of mix design and testing parameters, (ii) replicability of rheological or mechanical data, and (iii) consistency of curing and reporting protocols. Disagreements were resolved through discussion. Studies lacking sufficient experimental detail were excluded.

(4) Bibliometric mapping (VOSviewer)

The curated set is analysed to reveal keyword co-occurrence, co-authorship, and citation structures. These maps provide the quantitative foundation required by PRISMA for transparency and guided the subsequent mechanistic synthesis, which integrates material composition, pozzolanic chemistry, rheology, and sustainability.

(5) Evidence synthesis and interpretation

Findings from the maps are integrated with a close reading of the shortlisted studies. Key variables (mix design, W/G, additives, curing time, test methods, rheological models, and unconfined compressive strength (UCS)/elastic parameters, regardless of measurement method or testing age) are extracted and compared. A narrative is then developed, highlighting trends, methodological patterns, and unresolved questions.

Publication selection workflow (Scopus-based)

Phase 1: Initial search

Articles on cementitious grout properties published from 2006 to 2025 were retrieved from the Scopus database. Queries were constructed with Boolean operators ("AND", "OR", "NOT") and executed in TITLE-ABS-KEY. PRISMA-P guidance was followed [20]. Using the inclusive string grout AND rheology AND ground reinforcement, a total of 245 publications were returned.

Phase 2: Refining the search

Subject categories in Scopus were reviewed, and non-relevant domains were removed. Records labelled as conference proceedings, early-access items, editorials, notes, and review articles were excluded to prioritise peer-reviewed journal papers, which are generally regarded as the most authoritative, impactful, and methodologically rigorous [21]. This screening yielded 161 publications. Restriction to English-language outputs was then applied, and one Chinese-language paper was excluded. Topic specificity was further increased by applying the following exclusion terms: Brick OR Brick powders OR Geopolymerization OR 3d-printing OR 3-d printing OR 3d printing OR 3d printers OR Sodium Compounds OR Geopolymer Concrete OR Geopolymer OR Geopolymers. After this refinement, 123 publications remained, forming a focused corpus aligned with the review topic. Searches were performed in June 2025 using the following Boolean query within the ALL fields:

ALL (grout AND Waste materials AND rheology AND ground reinforcement) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English") AND (EXCLUDE (EXACTKEYWORD,"Geopolymer") OR EXCLUDE (EXACTKEYWORD,"Geopolymers") OR EXCLUDE (EXACTKEYWORD,"Geopolymer Concrete") OR EXCLUDE (EXACTKEYWORD,"Sodium Compounds") OR EXCLUDE (EXACTKEYWORD,"3d-printing") OR EXCLUDE (EXACTKEYWORD,"3-d Printing") OR EXCLUDE (EXACTKEYWORD,"3d Printers") OR EXCLUDE (EXACTKEYWORD,"Brick Powders") OR EXCLUDE (EXACTKEYWORD,"Brick") OR EXCLUDE (EXACTKEYWORD,"3d Printing"))

These exclusions were applied to maintain a focused corpus centred on cementitious grouts used in reinforcement systems. Geopolymer and alkali-activated binders constitute a distinct research domain with different chemical mechanisms, performance drivers, and application contexts, which would have broadened the scope beyond the objectives of this review. Removing these terms therefore ensured that the final dataset remained thematically consistent with the study's focus on conventional cementitious grout behaviour in ground-support applications.

Phase 3: Manual selection

Titles, abstracts, and author keywords were evaluated by all reviewers against pre-specified inclusion criteria centred on the mechanical and rheological behaviour of cementitious grouts. Studies focused on adjacent but off-topic themes were set aside. For example, Abd et al. [22] studied the use of textile carbon yarns as a substitute for steel stirrups in reinforced-concrete beams and the focus was placed on shear reinforcement performance of reinforced concrete beams, not on the mechanical or rheological behaviour of cementitious grouts. For this reason, the paper and studies of a similar nature was excluded from the review corpus. Following this screening, 101 journal articles were retained for detailed analysis.

Phase 4: Bibliometric analysis

The corpus of 101 studies was examined using VOSviewer (v1.6.20) for bibliometric mapping. Co-authorship links, keyword co-occurrence, and citation relationships were visualised, and thematic clusters were identified [23]. From these networks, trends in publication volume, leading outlets, active institutions, and topical hotspots were inferred. Alternative platforms—Bibliometrix, SciMAT, CitNetExplorer, BibExcel, and Pajek—were noted as complementary options for data retrieval and exploratory verification.

All searches can be reproduced directly in Scopus using the Boolean query, filters, and retrieval date provided above.

3. Analysis and Results

3.1. Descriptive Results

3.1.1. The Trend of Research on the Characteristics of Cementitious Grouts

Figure 2 summarises the long-term evolution of cementitious-grout research from 2006 to 2025. While the field began slowly, showing only isolated publications between 2006 and 2014 and again in 2016, the steady rise in output after 2018 marks a clear turning point. Annual publications remained below two papers until 2018 but increased markedly from 2019 onward, reaching a pronounced peak in 2024 and sustaining high activity into 2025. Citation patterns follow a similar trajectory; the dataset accumulates 1874 citations overall, with notable surges in 2019, 2022, and 2023. Years with low output but high citation density, such as 2015 and 2019, indicate that a small number of influential studies helped establish foundational concepts that later catalysed the rapid growth phase. These influential contributions include early work on grout microstructure and pozzolanic enhancement published in 2015, as well as widely referenced studies from 2019 that advanced rheological characterisation and modelling of grout–rock–bolt interaction, which collectively shaped subsequent research directions. Overall, the combined publication–citation trend reflects the transition from an emerging research niche to a more established and rapidly expanding investigative area.

The geographical distribution of the literature presented in Figure 3 indicates that research productivity is concentrated in a small number of regions, reflecting differences in national investment in underground construction and mining research. Rather than listing numerical outputs, the figure highlights the broader pattern: China, Australia, and the United States form the core contributors, with emerging activity in Europe and the Middle East. These regional clusters correspond to jurisdictions with active tunnelling programmes, strong cementitious materials research, or significant mining sectors. As discussed in Section 3.1.3, the analysis of institutional contributions refines this view by identifying specific institutional hubs-such as major engineering universities-illustrating how national contributions translate into organisational research strength.

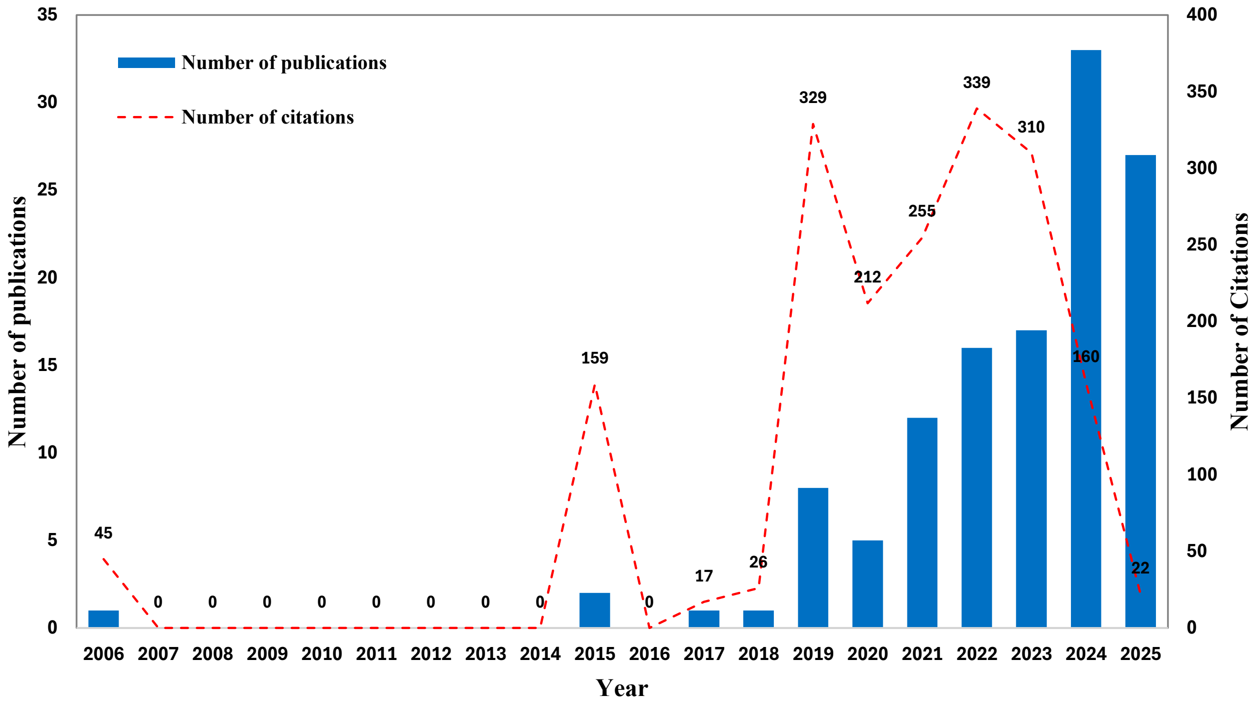

Figure 2. Publications and citations of articles during 2006–2025.

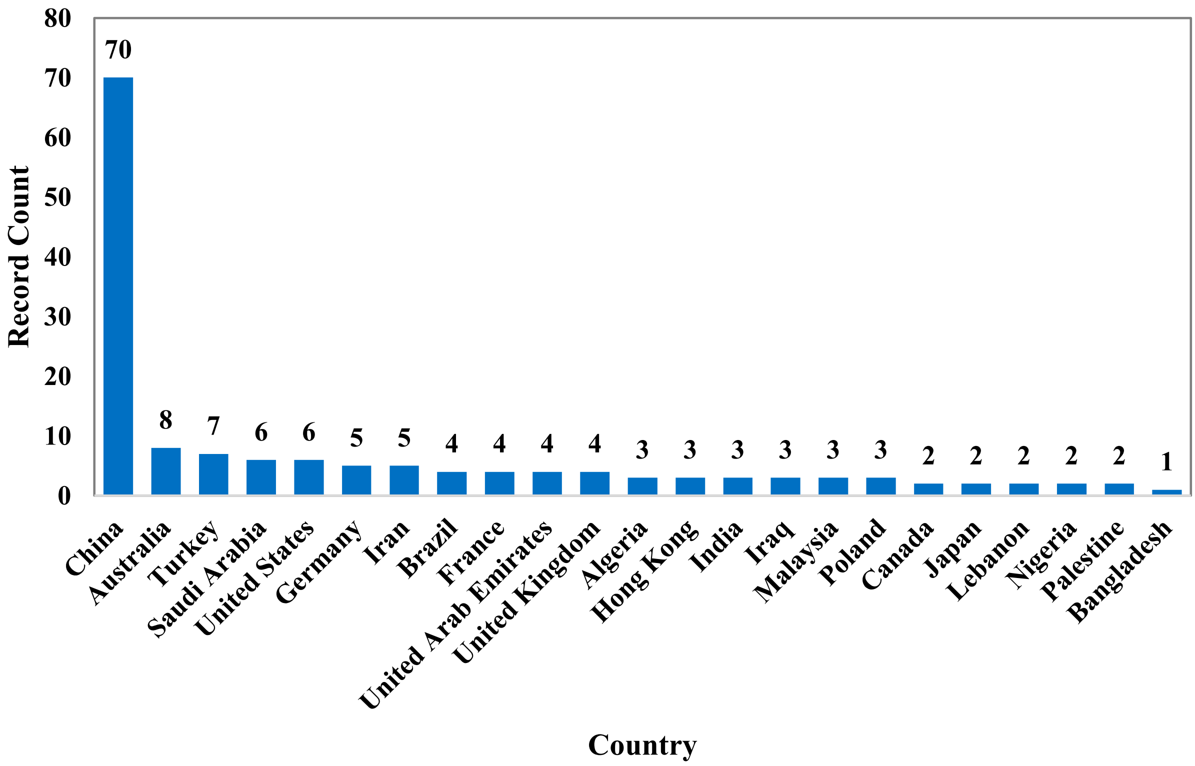

Figure 3. The number of published articles in different countries.

3.1.2. Journal Outlets Leading Research on Characteristics of Cementitious Grouts

A citation-based journal analysis was undertaken to identify the principal outlets for the topic. With a minimum threshold of one paper per source, the top ten journals out of 46 journals are listed in Table 1. Construction and Building Materials leads decisively with 28 publications and 771 citations. Two further Elsevier titles, "Journal of Building Engineering" and "Case Studies in Construction Materials", follow with 8 and 7 papers and 145 and 150 citations, respectively. Collectively, these three journals account for

43 of the 62 papers and the vast majority of citations, indicating a strong concentration of influence within Elsevier's portfolio. Additional contributions come from Materials and Buildings, as well as Applied Sciences (Switzerland), though their citation totals remain modest. Specialist venues such as Advances in Cement Research, Advances in Materials Science and Engineering, Arabian Journal for Science and Engineering, and Journal of Sustainable Cement-Based Materials appear with smaller but complementary footprints. Impact factors span 1.3–8.0, with the leading trio positioned at the upper end, consistent with their prominence in both output and impact.

Table 1. Top 10 contributing journals in the field in Scopus (2006–2025).

ID	Journal	Number of Publications	Total Citations	Impact Factor	Publisher
1	Construction and Building Materials	28	771	8.0	Elsevier—Amsterdam, Netherlands
2	Journal of Building Engineering	8	145	7.4	Elsevier
3	Case Studies in Construction Materials	7	150	6.6	Elsevier
4	Materials	6	28	3.2	MDPI—Basel, Switzerland
5	Buildings	3	9	3.1	MDPI
6	Advances in Cement Research	2	10	1.3	ICE Publishing—London, UK
7	Advances in Materials Science and Engineering	2	3	--	John Wiley and Sons—Hoboken, NJ, USA
8	Applied Sciences (Switzerland)	2	9	2.5	MDPI
9	Arabian Journal for Science and Engineering	2	17	2.9	Springer—New York City, NY, USA
10	Journal of Sustainable Cement-Based Materials	2	3	4.2	Taylor and Francis—London, UK

3.1.3. Institutions Leading Research on Characteristics of Cementitious Grouts

The co-authorship and institutional output patterns reveal a research landscape dominated by a small number of well-connected academic hubs. The institutional network shown in Table 2 highlights how national research capacity translates into organisational influence. Chinese universities form the central backbone of the network, reflecting China's sustained investment in cementitious materials and underground construction research. Within this group, several institutions act as high-impact nodes, characterised by strong citation profiles and extensive collaborative links. Notably, contributions from Turkey and Australia also stand out, indicating that while the network is China-centred, it remains internationally connected through partnerships that bridge regional research communities. This distribution suggests that institutional leadership and collaboration intensity, rather than output volume alone, are key drivers shaping knowledge development in the field.

Table 2. Top 10 contributing institutions in Scopus (2006–2025).

ID	Institution	Number of Publications	Total Citations	Country
1	Shandong University	5	170	China
2	Anhui Jianzhu University	4	9	China
3	University of Science and Technology Beijing	4	47	China
4	The University of Western Australia	3	153	Australia
5	Anhui University of Science and Technology	3	64	China
6	Gaziantep University	3	200	Turkey
7	Harbin Institute of Technology	3	160	China
8	Southeast University	3	133	China
9	China University of Mining and Technology	3	14	China
10	Nigde Omer Halisdemir University	3	13	Turkey

3.1.4. Researchers Leading Research on Characteristics of Cementitious Grouts

VOSviewer was applied to examine the main contributors within this research domain. Through the analysis of co-authorship patterns, the dataset highlighted collaboration among 449 authors focusing on studies of cementitious grouts. By applying a threshold of at least two publications per researcher, 41 core authors were identified, with the ten most influential presented in Table 3. Among them, Celik Fatih appears as the most productive scholar with five publications and 189 citations. In comparison, Canakci Hanifi, while publishing three papers, has achieved the highest citation impact with 200 citations, positioning him as the most referenced author in the field.

Table 3. Top 10 contributing authors in Scopus (2006–2025).

ID	Author	Institution	Number of Publications	Total Citations
1	Celik, Fatih	Nigde Omer Halisdemir University, Turkey	5	189
2	Canakci, Hanifi	Gaziantep University, Turkey	3	200
3	Zhang, Qingsong	Shandong University, China	3	127
4	Cinar, Muhammet	Kahramanmaras Sutcu Imam University, Turkey	3	47
5	Wang, Kai	Henan University, China	3	24
6	Yıldız, Oguzhan	Nigde Omer Halisdemir University, Turkey	3	13
7	Colak, Andac Batur	Nigde Omer Halisdemir University, Turkey	3	13
8	Golewski, Grzegorz Ludwik	Lublin University of Technology, Poland	2	136
9	Huo, Wangwen	Southeast University, China	2	132
10	Pu, Shaoyun	Southeast University, China	2	132

The co-authorship network in Figure 4 shows seven distinct co-authorship clusters, which reveal how collaboration structures shape knowledge development. A small number of tightly connected author groups dominate the network, forming central hubs with high total link strength. These hubs bridge thematic clusters and support the diffusion of grout-related knowledge across regions. In contrast, several peripheral nodes indicate independent or emerging research groups that contribute to niche methodological advances. This network structure suggests that collaboration intensity is a major driver of publication influence within this field.

Figure 4. Co-authorships between top researchers in the field of characteristics of cementitious grouts.

Beyond the visual clustering, quantitative network indicators reinforce the strength of collaborations. The co-authorship network generated by VOSviewer yielded a total link strength (TLS) of 312 across 41 core authors, with an average degree centrality of 7.6 connections per author. The largest collaborative group (Cluster 1) exhibits a TLS of 96, indicating strong internal cohesion and sustained co-publication activity. Authors such as Fatih Celik and Hanifi Canakci show the highest degree centrality ($\geq$12 links), reflecting their role as bridging nodes that connect multiple research groups. These metrics support the qualitative interpretation of collaboration patterns and confirm that several high-impact authors anchor the global research network on cementitious grouts.

Red cluster: This cluster includes the collaborative work of Dai, Hu, Liao, Lin, and Li, who have investigated the synergistic use of graphene oxide (GO) and fly ash (FA) in cementitious grouts. Their studies, published in 2024 and collectively cited 20 times, highlight that GO–FA composites exhibit superior flowability, stability, and mechanical performance compared with traditional cementitious grouts. Beyond mechanical enhancement, their findings indicate that the combined incorporation of FA and GO reduces cement consumption, thereby contributing to sustainability, while simultaneously improving durability and strengthening grout–rock interface bonding, as confirmed through experimental testing and microstructural characterisation.

Green cluster: This cluster consists of Song, Zhu, Wan, Huo, and Pu, who collaborated on advancing alkali-activated materials as sustainable substitutes for conventional cementitious grouts. Their investigations explored the use of fly ash, ground granulated blast-furnace slag, and steel slag in alkali-activated grouts and binders, demonstrating improvements in workability, strength, durability, and microstructural refinement compared with ordinary Portland cement systems. Published between 2020 and 2022, their two joint papers have attracted a remarkable 132 citations, underscoring the strong impact and relevance of their contributions to the field.

The Blue cluster is represented by the joint contributions of Ouyang, Yi, Sun, Wang, and Mo, who examined excess-sulphate phosphogypsum slag–based grouts for complex ground conditions. Their two publications (2024–2025), which together have attracted six citations, address both material modification and practical application: one study demonstrated that partial replacement with calcium sulfoaluminate cement markedly improves the underwater stability and mechanical performance of grouts in karst environments, while the other developed a predictive model to guide groutability in coral sand foundations. These works underscore the cluster's focus on tailoring grout formulations and predictive tools for challenging geological settings.

The Purple cluster brings together the contributions of Sun, Wang, Peng Liu, and Kaiwei Liu, whose joint research has advanced sustainable grouting technologies. Through two papers published between 2023 and 2024, which have collectively accrued six citations, they explored strategies to mitigate rapid solidification and shrinkage in alkali-activated slag cements as well as optimised double-liquid grout formulations incorporating industrial by-products. Their findings not only address key barriers to the engineering application of alkali-activated binders but also propose resource-efficient designs that enhance performance and durability, underscoring the cluster's impact on sustainable material development.

Light green cluster: Celik, Colak, Yildiz, and Bozkir have contributed to advancing knowledge on the rheological and workability behaviour of cementitious grouts through the incorporation of nanoparticles such as nanoalumina, nanosilica, and nano-titania in conjunction with fly ash. Their collaborative studies examined the influence of these additives on parameters including flow characteristics, viscosity, and yield stress, with outcomes reported across three publications between 2022 and 2025, which collectively received 13 citations. While Bozkir was involved in only one of these works, all three studies integrated artificial neural network approaches to reliably predict grout performance based on the experimental datasets.

The Light Blue cluster is defined by the collaboration of Qingsong Zhang and Huasheng Zhang, whose work has advanced alternative grout systems through two influential publications between 2022 and 2023, together cited 39 times. Their studies addressed the compatibility of superplasticisers with biomass-activated grouts and examined the injectability of seawater-mixed magnesium phosphate cement slurries, offering insights into both performance optimisation and practical application.

3.1.5. Articles Leading Research on Characteristics of Cementitious Grouts

Based on citation analysis, Table 4 presents the most impactful contributions in the field. For this purpose, only studies that achieved a minimum of 64 citations were retained, resulting in the identification of eight highly referenced papers focusing on the properties and performance of cementitious grouts. These highly cited studies were published across five different journals. Among them, "Construction and Building Materials" was the clear leader, contributing four papers. The remaining articles appeared in "Energies", "Polymers", "Journal of Building Engineering", and "Structural Concrete", each represented by a single publication.

As presented in Table 4, eight highly cited studies addressed the characteristics and performance of cementitious grouts between 2006 and 2025. The methods applied in these studies varied, encompassing laboratory experimental investigations, field validation, and machine learning modelling. In terms of experimental contributions, several papers investigated modifications to cementitious systems using supplementary or alternative materials. Celik, Canakci [24] examined the influence of rice husk ash (RHA) on grout rheology, reporting that increasing RHA content enhanced viscosity and yield stress while reducing slump, with shear-thickening behaviour emerging at high replacement levels. Song et al. [25] demonstrated that ternary blends of steel slag and GGBS in alkali-activated fly ash pastes improved strength and pore refinement, with 40% Steel Slag (SS)–GGBS content offering optimal flexural performance. Complementing this, Golewski [26] reported synergistic benefits of nanosilica (nS) and coal fly ash (CFA), where a blend of 5% nS and 15% CFA enhanced compressive and tensile strength by over 35% compared to control mixes. Afroughsabet et al. [27] focused on Calcium sulfoaluminate (CSA) cement systems, highlighting mechanical improvements and reduced shrinkage but also increased carbonation and corrosion susceptibility, particularly in ternary mixes with OPC and GGBS. Similarly, Aslani, Gedeon [28] showed that introducing crumb rubber and fibres into self-compacting concretes reduced workability but enhanced tensile performance when steel fibres were incorporated.

The influence of the eight most cited studies extends beyond their citation counts and reflects their contributions to key methodological and practical advances in grout research. High-impact papers typically introduced either novel experimental protocols, such as improved approaches for quantifying rheology, bleeding, or microstructural evolution, or innovative mix designs incorporating SCMs that enhanced sustainability while maintaining mechanical performance. Others are widely cited because they offer transferable frameworks for modelling hydration, bond mobilisation, or early-age behaviour, making them useful across both research and industry. Several studies also gained prominence due to their direct applicability to underground construction and mining, where reliable reinforcement and pumpability are critical. Collectively, these influential works shaped the field by providing robust methods, validated mechanistic explanations, and practical solutions that continue to underpin current research directions.

Other studies explored innovative grout formulations. Zhang J et al. [29] developed a cementitious anti-washout grout combining cement, water glass, and xanthan gum, which demonstrated short set times, high early strength, and superior anti-washout properties validated in field applications for karst inrush control. Wang, Liu [30] modified cement grout with water-soluble epoxy resin, showing reduced bleeding, improved strength, and enhanced bonding through the formation of a Ca^{2+}–OH cross-linked network.

In parallel, data-driven methods have also been applied. Nafees et al. [31] employed machine learning approaches, including decision trees and support vector machines (SVM), to predict compressive strength of silica-fume concretes. Their results confirmed that decision trees offered higher accuracy than SVM, with ensembles further improving predictive capability, and cement and water were identified as the most critical influencing factors.

Additional evidence from studies on sustainable composite materials demonstrates how alternative constituents can influence mechanical behaviour, pore structure, and long-term performance in systems related to cementitious matrices. Silva et al. [32] reported that incorporating recycled PET into soil–cement bricks improves compressive strength while reducing density and environmental footprint, illustrating how polymeric waste can modify packing and enhance internal bonding. Brito et al. [33] showed that natural clay–manure blends influence moisture regulation, workability, and durability in adobe blocks through microstructural refinement and improved fibre–matrix interaction. Although these materials differ from cementitious grouts, the underlying mechanisms-changes in particle arrangement, void structure, and moisture sensitivity-offer relevant insights for designing sustainable grout mixtures that balance performance with reduced environmental impact.

Table 4. Most frequently cited studies examining the characteristics of cementitious grouts in Scopus (2006–2025).

ID	Author(s)	Main Topic	Journal	Citations	Method	Major Findings
1	Celik, Canakci [20]	An investigation of rheological properties of cementitious grout mixed with rice husk ash (RHA)	Construction and Building Materials	159	Laboratory experimental investigation	Increasing RHA (5–30%) raised Marsh cone time, plate cohesion, plastic/apparent viscosity and yield stress, while reducing mini-slump; at high RHA and w/b > 1.00, mixtures exhibited shear-thickening and pseudoplastic behaviour.
2	Song et al. [21]	Efficient use of steel slag in alkali-activated fly ash-steel slag-ground granulated blast furnace slag ternary blends	Construction and Building Materials	102	Laboratory experimental investigation	SS–GGBS slightly prolonged setting yet improved initial flow/viscosity control; increased compressive strength at early and later ages; reduced brittleness with an optimal 40% SS–GGBS for flexural strength; microstructure showed more amorphous gels, pore refinement, and lower total porosity, explaining strength gains.
3	Golewski [22]	Combined Effect of Coal Fly Ash (CFA) and Nanosilica (nS) on the Strength Parameters and Microstructural Properties of Eco-Friendly Concrete	Energies	99	Laboratory experimental investigation	Combined nS (5%) and CFA (0, 15 and 25%) synergistically improved microstructure (pore/crack filling) and mechanical properties; optimal 5% nS + 15% CFA raised 28-day compressive and splitting tensile strengths by 37.68% and 36.21% versus control; supports lower-carbon blended cements up to 30% replacement.
4	Nafees et al. [27]	Modelling of Mechanical Properties of Silica Fume-Based Green Concrete Using Machine Learning Techniques	Polymers	91	Machine learning modelling	Built ML models (DT, SVM; ensembles) on 283 tests using six mix inputs; DT outperformed SVM; ensembles improved accuracy (11% for DT; 1.5% for SVM); cement and water were the most influential variables; cross-validation confirmed generalisable performance.
5	Li et al. [25]	Investigation and practical application of a new cementitious anti-washout grouting material	Construction and Building Materials	88	Laboratory experimental and field investigation	CIS (cement + water glass + xanthan gum) showed short set time, high early strength, high viscosity and retention, and non-toxicity; outperformed conventional cement–water-glass grout; XRD/MIP/IR/SEM evidenced denser microstructure; grouting-parameter design method proposed from setting-time/viscosity evolution; field application effectively controlled water inrush.

Table 4. *Cont.*

ID	Author(s)	Main Topic	Journal	Citations	Method	Major Findings
6	Wang, Liu [26]	Investigation on fundamental properties and chemical characterisation of water-soluble epoxy resin modified cement grout	Construction and Building Materials	71	Laboratory experimental investigation	Epoxy addition lowered bleeding and initially enhanced fluidity/retention; reduced particle size and induced electrostatic attraction (zeta potential) between phases; markedly increased UCS, splitting tensile strength and ultimate strain (reduced brittleness); boosted bonding; epoxy promoted hydration but excess epoxy formed films limiting further hydration; mechanism attributed to Ca^{2+}–OH reactions forming a cross-linked network.
7	Afroughsabet et al. [23]	Investigation of the mechanical and durability properties of sustainable high-performance concrete based on calcium sulfoaluminate cement	Building Engineering	65	Laboratory experimental investigation	CSA substitution enhanced mechanical properties and reduced shrinkage; increased carbonation susceptibility and steel corrosion risk; binary/ternary CSA–OPC–GGBS mixes lowered strengths and durability vs. pure CSA; SEM indicated ettringite decomposition and formation of carbonated phases.
8	Aslani F, Gedeon [24]	Experimental investigation into the properties of self-compacting rubberised concrete incorporating polypropylene and steel fibres	Structural Concrete	64	Laboratory experimental investigation	Replacing 20% fine aggregate with crumb rubber and adding PP/steel fibres degraded fresh/rheological properties (steel > PP impact); PP fibres slightly reduced compressive strength and had limited effect on splitting tensile; steel fibres marginally increased compressive strength and improved splitting tensile with dosage.

3.2. Research Hotspots on Characteristics of Cementitious Grouts

In this review, a total of 1200 keywords were initially identified. By setting a minimum occurrence threshold of five, 62 keywords satisfied the criterion for further analysis. For these keywords, VOSviewer computed the total strength of their co-occurrence links with other terms, allowing the identification of those with the greatest connectivity as the most influential within the network. Subsequently, refinements were made to ensure accuracy and thematic clarity. Broad and generic expressions such as cement, cements, concrete, coal, coal mines, and durability were excluded, as their generality could obscure specific research directions. Semantically overlapping terms were merged into single representative categories. For instance, fluidity and flowability were standardised as workability; plastic viscosity, viscosity, rheology, and yield stress were unified as rheological properties; material terms such as fly ash, silica fume, and ground granulated blast furnace slag were combined as supplementary cementitious materials; and strength, bending strength, and compressive strength were grouped under mechanical properties. Likewise, construction-related terms (concrete beams and girders, concrete mixtures, and concrete construction) were consolidated as reinforcement. Through this process, the refined mapping set comprised 28 focused, high-impact keywords, providing a concise and coherent basis for analysis. Ultimately, the refined co-occurrence network comprised 28 high-impact keywords, which VOSviewer grouped into two clusters connected through 19 links and a TLS of 206, as illustrated in Figure 5.

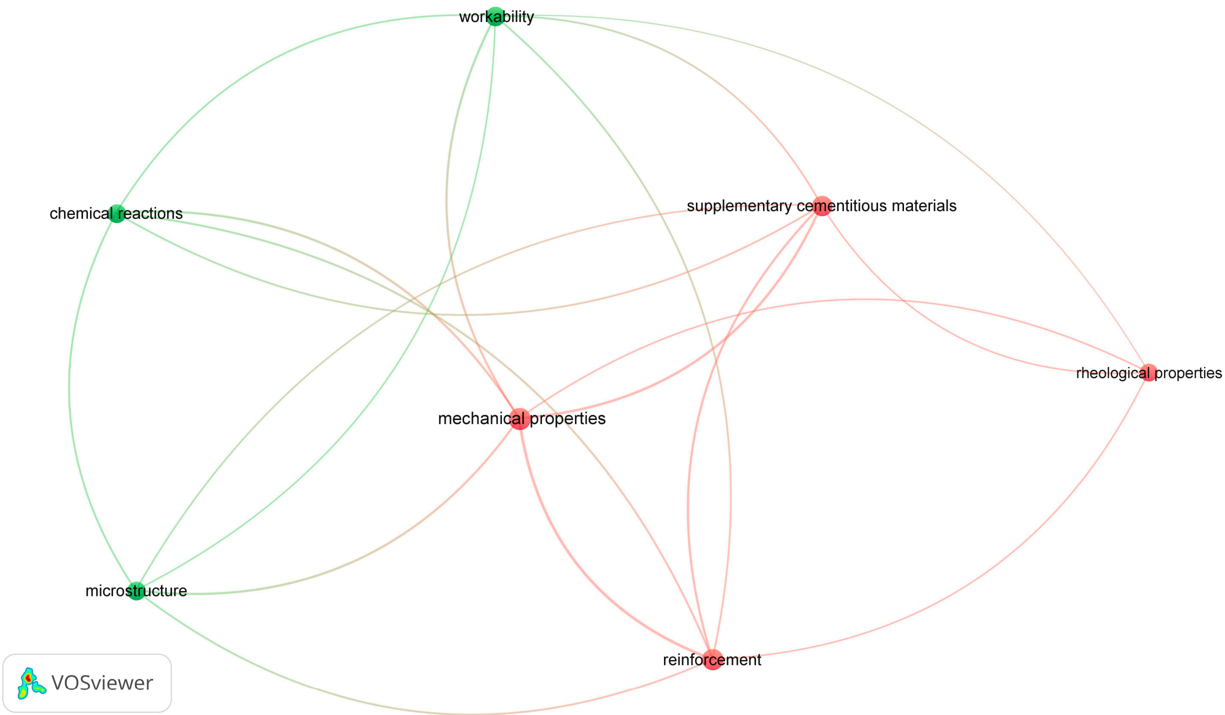

Figure 5. Co-occurrence mapping network of research hotspots tied to characteristics of cementitious grouts; colours denote distinct keyword clusters automatically generated by VOSviewer.

Cluster 1 contains 16 nodes and exhibits the highest connectivity (TLS = 148), indicating that reinforcement, mechanical properties, supplementary cementitious materials, and rheological behaviour form the dominant research stream. Cluster 2 contains 12 nodes with a TLS of 58 and is centred on workability, chemical reactions, and microstructure. These indicators confirm that Cluster 1 constitutes the structural backbone of the literature, functioning as the central hub through which most keyword relationships pass, while Cluster 2 forms a complementary but less densely connected thematic space. The total link strength, node counts, and cross-cluster connections provide quantitative evidence of the prominence and interdependence of these research hotspots, substantiating their relevance beyond simple co-occurrence frequency.

3.2.1. Reinforcement Mechanisms in Ground Support

The primary purpose of reinforcement systems in underground excavations is to enhance the stability of the surrounding rock mass and prevent the detachment of blocks or wedges that could compromise excavation safety. Rock reinforcement can generally be classified into active and passive systems. Active methods apply support directly against the rock surface, such as mesh, steel sets, or sprayed concrete, whereas passive reinforcement interacts with the rock mass through an anchoring mechanism that mobilises confinement and shear resistance along potential failure planes [34,35]. Among passive systems, rock bolts, cable bolts, and ground anchors have become standard technologies, differing mainly in embedment length: rock bolts are typically less than 3 m, cable bolts range from 3 to 10 m, and ground anchors often exceed 10 m in length [36,37].

Rock bolting systems are further distinguished by the interaction mechanism between the bolt and the surrounding rock. Three categories are generally recognised: mechanically anchored bolts, which rely on expansion shells to create immediate end anchorage; frictional bolts, such as Split Sets and Swellex, which generate radial contact pressure along the borehole; and FGRBs, where a cementitious or resin grout forms a continuous bond between the bolt and the rock [38,39]. Mechanically anchored systems provide rapid support but are vulnerable in weak or highly fractured ground, while frictional bolts are valued for their energy absorption in squeezing conditions. Fully grouted bolts, however, have become the dominant technology due to their versatility, ability to perform in highly jointed rock, and superior long-term stiffness and bond strength [39,40].

The mechanism of load transfer in reinforcement is controlled by the relative stiffness of bolt, grout, and rock mass, and by the shear and tensile strength of the interfaces involved. Studies consistently identify the bolt–grout interface as the most common location of debonding, especially under axial tension, although grout–rock failure and grout column shear are also reported depending on ground conditions and grout quality [41]. Laboratory pull-out testing, complemented by numerical simulations, has clarified how stress redistributes along the bolt length, typically mobilising a peak shear resistance near the collar that decays toward the free end [42]. Shear tests further demonstrate that grout confinement plays a crucial role in resisting slip, with increases in normal pressure leading to higher bond strength and energy absorption [43].

Cable bolts extend the principles of rock bolting to greater depths and larger spans. Their performance is strongly influenced by grout stiffness, borehole diameter, and installation quality. Hyett et al. [38] demonstrated that both load capacity and stiffness improve substantially when the water-to-grout ratio is kept below 0.4, while Mirza et al. [44] confirmed that strength development is directly linked to curing time, with compressive strength rising consistently from 1 to 28 days. Comparative pull-out studies have shown that bar bolts often display higher stiffness than stranded cable bolts due to more uniform stress transfer at the steel–grout interface [45].

Modern developments in reinforcement systems have sought to increase both capacity and deformability, leading to the introduction of energy-absorbing bolts. Chunlin Li C [39] described the design of yielding bolts capable of accommodating large displacements without losing anchorage, a major advance in seismically active or burst-prone mines. At the same time, advances in monitoring have transformed the understanding of reinforcement behaviour. Fibre-optic distributed sensing has been successfully integrated into fully grouted bolts to record strain distribution along the embedded length, enabling direct observation of progressive debonding and load redistribution [46]. Such techniques not only validate numerical simulations but also provide new pathways for adaptive support design in highly variable ground conditions.

These developments demonstrate that reinforcement mechanisms are not limited to the bolt itself but represent a composite system integrating steel, grout, rock mass, and installation method. This system perspective has become increasingly prominent in recent decades, with emphasis on the coupling between material science innovations (high-performance grouts and resins), structural design of reinforcement elements, and advanced monitoring technologies.

3.2.2. Cementitious Grouts

Grouts not only provide the essential encapsulation for reinforcement elements but also increasingly serve as a platform for advancing sustainability in ground support systems. The grout column forms the interface between bolt and host rock, and its integrity is crucial for load transfer, stiffness, and durability. It must therefore meet multiple performance criteria: injectability during placement, strength development in the hardened state, and resistance to chemical and mechanical degradation during service life. Beyond these conventional roles, grouts are now being engineered as composites that integrate SCMs, waste-derived binders, and novel admixtures to address both technical and environmental challenges.

Ordinary Portland cement remains the most widely used binder in encapsulation systems due to its availability and low cost. Its role in defining the mechanical and shear performance of reinforced systems has long been recognised. Studies show that W/G controls porosity and compressive strength: lower ratios yield higher UCS but reduce workability [47]. Mirzaghorbanali et al. [44] reported that curing time further enhances UCS while Moosavi, Bawden [43] demonstrated through direct shear testing that the shear strength of Portland cement grouts increases under confining pressure, underscoring the grout's contribution to resisting interface slip. These findings reinforce the importance of cementitious grouts as the baseline material against which new innovations are benchmarked.

In high-stress or seismically active environments, resin-based capsules are often used because of their rapid curing and early strength. Resin encapsulation provides high initial bond stiffness, enabling reinforcement to carry load immediately after installation. Hyett et al. [42] highlighted that resin-grouted bolts mobilise bond strength much faster than cementitious systems. However, resins are costlier and can degrade under elevated temperatures. Nourizadeh et al. [40] investigated resin encapsulation at high temperatures and reported significant strength loss above 80 °C, which raises concerns in deep or geothermal applications. These results suggest that while resins are invaluable for immediate support, their long-term durability under aggressive environments remains a research focus.

The integration of SCMs has emerged as a major hotspot within bibliometric clusters, where mechanical properties, rheological behaviour, and supplementary cementitious materials intersect. SCMs reduce reliance on Portland cement while enhancing performance. Dong et al. [48] demonstrated that GGBS improves both mechanical integrity and durability of cementitious grouts while lowering the carbon footprint. Zhao et al. [49] investigated modified magnesium-based binders and reported that industrial by-products can be used to tailor rheological behaviour, ensuring more effective encapsulation.

A strong emphasis has also been placed on recycled ashes. Yuan et al. [9] explored the utilisation of municipal solid waste incineration ash in cementitious grouts and observed competitive compressive strength and acceptable rheological properties compared to conventional mixes. Dai et al. [50] investigated multi-source SCMs including fly ash and silica fume, showing synergistic effects that enhance both workability and mechanical capacity. The relevance of these findings is underscored by the bibliometric analysis, where SCM-related keywords emerged as central connectors linking material innovation with reinforcement performance.

In line with sustainability imperatives, researchers are investigating waste-derived binders beyond traditional fly ash and slag. Yuan et al. [9] confirmed that incineration ash alters hydration kinetics, promotes secondary calcium silicate hydrate (C–S–H) formation, and refines pore structure. Other studies have highlighted the potential of agricultural ashes such as rice husk ash and metakaolin-based systems, which contribute reactive silica and alumina for pozzolanic activity [51]. These findings establish waste-derived grouts as both environmentally beneficial and technically competitive, aligning ground support practices with global sustainability targets.

Encapsulation quality depends as much on fresh-state rheology as on hardened strength. Grouts must exhibit adequate fluidity to penetrate boreholes and achieve intimate contact with bolt surfaces, yet sufficient stability to resist bleeding and segregation. Rheological models describe grouts as Bingham fluids characterised by yield stress and plastic viscosity, which dictate flow under shear [52]. Zhao et al. [49] emphasised that adjusting rheological parameters in magnesium-based grouts ensured uniform encapsulation without voids. Dong et al. [48] found that GGBS incorporation stabilised these properties during injection, reducing the risk of incomplete bonding. These studies confirm that rheological optimisation is essential to guarantee encapsulation effectiveness.

While cementitious grouts were historically optimised for steel bolts, the increasing use of fibre-reinforced polymer (FRP) and fibreglass reinforcements introduces new encapsulation challenges. Gregor et al. [53] investigated the shear behaviour of fibreglass bolts encapsulated in cementitious grouts and found that bond capacity is highly dependent on grout composition and pretension levels. These results indicate that grout formulations may need to be tailored for compatibility with different reinforcement materials, as bond mechanisms for composites differ from those for steel.

3.2.3. Chemical Reactions and Pozzolanic Reactivity

The chemistry that unfolds once grout meets water governs how effectively a reinforcement element is encapsulated and how that encapsulation endures under load and environment. In our co-occurrence map, this thread sits in Cluster 2 (chemical reactions and microstructure): hydration and secondary reactions reorganise ions in the pore solution, precipitate new hydrates, and progressively refine the solid skeleton that transfers load from steel to rock. In OPC grouts, early reactions are dominated by alite and belite hydration to calcium silicate hydrate (C-S-H) and portlandite, with aluminate and ferrite phases competing for sulphate to form AFt/AFm phases; these pathways are well established and provide the baseline against which blended and alternative binders should be interpreted [54].

Supplementary cementitious materials reshape these pathways in two principal ways. Pozzolans (e.g., fly ash, silica fume, and metakaolin) consume portlandite released by clinker hydration and generate additional C-S-H (and, where Al is available, C-A-S-H), while latent-hydraulic materials such as GGBS hydrate in alkaline, Ca-rich environments to yield C-(A)-S-H directly. The result is a different pore solution chemistry (lower [$Ca(OH)_2$], altered alkali balance) and a modified hydrate assemblage, often with reduced capillary porosity and a denser interfacial transition zone around steel or cable strands. Recent synthesis papers provide a consolidated view of these mechanisms and their performance implications across SCM families [8].

Because pore solution dictates which hydrates are stable, its evolution under SCM addition is central to grout design. Systematic measurements show that blended systems depress Ca^{2+}/OH^- concentrations and enrich alkalis and alumina, thereby favouring AFm variants and Al-bearing C-A-S-H over portlandite-rich assemblages typical of neat OPC [55]. This chemical shift also conditions external ion interactions. In chloride-bearing groundwaters, for example, AFm phases partially convert to Friedel's salt, and chloride uptake includes both chemical binding (AFm/Friedel's) and physical sorption on C-(A)-S-H; the balance is strongly pH- and Al-content-dependent [56].

Within our dataset, several recent grout-focused studies illustrate how industrial by-products steer hydration. A study on coal-derived solid-waste grouts reported concurrent formation of AFt/AFm with C-S-H, but with reaction rates and phase proportions controlled by additive chemistry and fineness, evidence that secondary aluminosilicate sources feed pozzolanic gel growth at the grout–rock interface [57]. Alkali-activated grout formulations designed from industrial residues further underscore the mechanistic split between high-calcium systems, which develop C-A-S-H and hydrotalcite-like phases, and low-calcium fly-ash blends, which form N-A-S-H networks; both chemistries can be tuned by activator modulus and dosage to balance setting with later-age stability [58]. In seawater-mixed magnesium-phosphate grouts, the reaction path is different again: acid–base reactions between MgO (or basic magnesium salts) and phosphate sources yield struvite-type hydrates (e.g., $MgKPO_4 \cdot 6H_2O$), whose rapid precipitation and low alkalinity alter interfacial chemistry and early bonding [59]. Together, these examples show how "encapsulation" is chemical before it is mechanical: the hydrate assemblage that forms in the first hours governs adhesion, creep, and subsequent resistance to leaching or ion ingress.

The pace at which pozzolans react matters in practice because grouting operations are time-sensitive. Metakaolin, with its highly disordered aluminosilicate structure, reacts quickly, scavenging portlandite and promoting early C-A-S-H and, under suitable Ca/Al, strätlingite; silica fume, dominated by amorphous SiO_2, accelerates CH consumption and drives a strong densification of the paste around reinforcement. These qualitative statements are backed by reactivity metrics and calorimetry. The rapid, relevant and reliable R3 protocol quantifies pozzolanic activity via heat release in simplified $Ca(OH)_2$–SCM–limestone systems, providing predictive links to strength and bound water [60]. At the molecular scale, C-S-H/C-A-S-H composition evolves with Si/Al/Ca and alkali uptake; rigorous thermodynamic and spectroscopic analyses capture how Al-for-Si substitution modifies gel topology and sorption sites [61,62].

Slag-rich systems used for low-heat, durable encapsulation exemplify latent-hydraulic behaviour. In alkaline, Ca-bearing pore solutions, GGBS dissolves to yield C-(A)-S-H and hydrotalcite-like phases; the kinetics and hydrate balance depend sensitively on slag chemistry. A pair of studies demonstrated that higher MgO content accelerated early reaction and strengthened hydrotalcite formation, whereas elevated Al_2O_3 favoured greater Al incorporation in C-(A)-S-H and modified setting/strength development [63,64]. In our dataset, slag-based grouting binders show the same signatures: autogenous shrinkage and rapid solidification correlate with activator chemistry and slag composition, and inert or weakly reactive fillers can temper heat release while preserving later-age gel development [65,66]. For OPC–slag blends used in conventional cementitious grout, the practical outcome is similar: lower early heat and CH content, higher later-age strength, and enhanced chemical binding capacity for deleterious ions, features that are attractive where consolidation grouting must coexist with aggressive groundwater.

The role of "waste-derived" aluminosilicates in tunnel grout chemistries is equally mechanistic. Recycled municipal solid-waste incineration ash has been adapted into low-cement printable binders, where reactive glassy phases and free lime participate in hybrid hydration/pozzolanic sequences that stiffen quickly yet continue to densify at later ages [9]. Calcium-carbide slag, rich in $Ca(OH)_2$ equivalents, can be blended with other residues to supply early alkalinity and Ca^{2+}, promoting AFt nucleation and secondary gel growth without excessive portlandite accumulation [50]. These findings map cleanly onto grout performance: faster percolation of a cohesive hydrate network improves early encapsulation, while the continued pozzolanic consumption of CH reduces permeability and chemical vulnerability at the steel–grout interface.

Where aggressive ions are present, the chemistry of the hydrate scaffold is not just formative but protective. Chloride binding is enhanced in Al-rich blended systems through both AFm conversion to Friedel's salt and increased uptake by C-A-S-H; this dual mechanism reduces free chlorides available for corrosion initiation, although binding equilibria remain sensitive to pH and competing anions [56]. Thermodynamic modelling gives a complementary vantage point for such questions, enabling phase-equilibria predictions across temperatures and blend chemistries relevant to tunnelling environments. Among other insights, modelling captures the temperature-driven conversion between AFt and AFm and the stabilising role of carbonate in AFm variants [67,68].

Finally, chemical control is inseparable from kinetics in the field. Accelerators, viscosity-modifying polymers, and seawater mixing alter early ionic speciation, nucleation rates, and hydrate identities. For example, hydroxypropyl-methylcellulose additions used to stabilise injection can retard aluminate dissolution and shift AFt/AFm balances while still permitting robust C-S-H growth [69]. In alkali-activated grout design, activator modulus and Na_2O content regulate silicate and aluminate release, synchronising set with pumpability and subsequent gel densification [56,70].

Across these systems, the common denominator is that the "best" grout chemistry for ground support is the one that coordinates ion release and hydrate precipitation to meet operational constraints (mixing, travel, set) while building a chemically resilient hydrate assemblage for the service environment. The literature now offers both mechanistic tools, pore-solution analysis, isothermal calorimetry, R^3 reactivity testing, and thermodynamic modelling, and grout-specific case studies to do exactly that, allowing chemical intent to be brought to the centre of encapsulation design rather than treated as an afterthought.

3.2.4. Fresh and Hardened State Properties

The performance of cementitious grouts in ground support is dictated not only by their chemical composition but also by their behaviour in both fresh and hardened states. During application, grouts must be sufficiently fluid to be injected into boreholes and fractures while maintaining stability to prevent segregation or bleeding. Once hardened, the material must provide the mechanical capacity to ensure effective load transfer between reinforcement elements and the surrounding rock. Consequently, evaluation of fresh-state parameters such as workability, consistency, stability, and bleeding is essential, while hardened-state properties are commonly characterised by compressive and flexural strength, shrinkage, and durability under chemical or hydraulic attack [71].

Workability is a critical measure of the grout's performance in its fresh state, reflecting its ability to flow cohesively without segregation of particles. This property depends on the interplay between fluidity and cohesion, which in turn are controlled by the water-to-binder ratio, aggregate type and grading, admixture dosage, cement chemistry, and temperature [72,73]. Experimental research confirms that supplementary cementitious materials (SCMs) substantially modify flow properties. For example, Kim et al. [74] reported that replacing ordinary Portland cement with raw fly ash increased flowability, whereas ground fly ash produced little effect. The addition of fine recycled-concrete aggregate reduced fluidity, although this could be compensated for with superplasticisers [75]. In contrast, rubberised grouts demonstrate consistently lower workability due to the hydrophobic nature of rubber and entrapped air, with reductions in fluidity scaling with increasing rubber content and particle size [76].

Bleeding is another critical property in the fresh state, reflecting the upward migration of water during sedimentation. Stable grouts should not exhibit more than 5% bleeding, with higher values indicating inadequate cohesion and a risk of void formation [77]. Studies consistently show that bleeding increases with higher water-to-binder ratios. Sha et al. [78] confirmed this relationship in grouts with ratios ranging from 0.6 to 1.2, noting that sedimentation directly influenced later strength variability. The incorporation of SCMs mitigates bleeding by refining particle packing and water demand. Perez-Garcia et al. [79] found that replacing 30–50% of cement with slag reduced bleeding across multiple slag types while maintaining flowability. Similarly, the combined use of GGBS and Class C fly ash decreased bleeding ratios, demonstrating that blend design can control sedimentation behaviour without compromising injectability [78]. Additives such as silica fume have been singled out as especially effective for bleeding control, outperforming bentonite and fly ash in comparative studies [80]. These findings are reinforced by dataset-based investigations, where sedimentation effects were directly linked to later mechanical variability [81].

Consistency, which indicates the ease with which grout can be deformed or spread, is often classified as fluid, plastic, or flowable and is commonly assessed by flow table or cone efflux tests. Krishnamoorthy et al. [82] evaluated grouts containing different SCMs using Marsh cone efflux times at water-to-binder (w/b) ratios of 0.25–0.40. They showed that superplasticiser demand increased with replacement level but could be reduced by adjusting water content, particularly in fly ash and slag mixes. This aligns with later rheological optimisation studies that mapped yield stress and viscosity across mix designs, providing quantitative consistency criteria for grout design [83].

Injectability represents a key fresh-state property, as it dictates whether grouts can penetrate fractures or voids in the rock mass. While often associated with flowability and stability, injectability is fundamentally governed by rheological properties. Studies emphasise that yield stress and plastic viscosity determine penetrability under pressure, while particle size distribution and stability control clogging risk [84]. Although detailed rheological considerations are treated in Section 3.2.5, it is clear from fresh-state evaluations that incomplete penetration due to poor injectability can compromise encapsulation quality regardless of grout strength.

The hardened state of cementitious grouts determines their ultimate ability to transfer loads from bolts or anchors into the surrounding rock. Compressive and flexural strength, modulus, and shear resistance are the principal indicators. Strength development is strongly influenced by water content and curing regime. Aziz et al. [47] reported that reducing W/G ratios increased UCS by producing denser microstructures, while Mirzaghorbanali et al. [44] confirmed continuous strength gain from 1 to 28 days in typical Australian industry mixes. Cable-bolt studies confirm that grout modulus and UCS strongly influence anchorage capacity, with load-bearing improvements of up to 70% observed when w/b ratios are kept below 0.4 [38]. Comparative testing of grouts for anchors highlighted that bar-type reinforcements exhibit higher stiffness than stranded cables, with differences controlled by grout–steel interfacial bond strength [45]. Direct shear testing of Portland cement grouts further confirmed that shear strength increases with confining stress [43]. Recent innovations have introduced alternative aggregates and modifiers to tailor hardened performance. Rubberised grouts, for instance, exhibit lower compressive and flexural strength compared with conventional mixes, yet their toughness is significantly enhanced. Yuan et al. [85] demonstrated that increasing crumb rubber content reduced strength but improved energy absorption, suggesting suitability for impact-prone or dynamic conditions.

Other research has focused on nano-modified grouts, where nanosilica additions refine microstructure, increasing compressive strength and decreasing permeability [11]. These findings reflect a wider shift towards designing hardened properties not only for static strength but also for durability, resilience, and compatibility with emerging reinforcement technologies.

The interplay of these properties is summarised in Table 5, which consolidates the key fresh and hardened parameters, their influencing factors, and reported performance outcomes from recent studies.

Table 5. Summary of fresh and hardened state properties of cementitious grouts used in ground support.

Property	Significance for Ground Support	Main Influencing Factors	Key Findings	References
Workability (flowability and cohesion)	Ensures grout can be pumped/injected without segregation	w/b ratio, SCM type, aggregate fineness, admixtures, temperature	Raw fly ash ↑ * flowability; ground fly ash minimal effect; recycled aggregate ↓ * flow but superplasticisers can restore; rubberised mixes markedly ↓ workability	Kim et al., 2018 [74] Mikos et al., 2021 [75] Siddika et al., 2019 [76]
Bleeding (stability)	Indicates risk of voids and weak encapsulation	w/b ratio, particle size distribution, SCM type, additives	Bleeding ↑ with w/b ratio; <5% is acceptable; slag and fly ash blends ↓ bleeding; silica fume most effective in minimising	Sha et al., 2019 [78] Perez-Garcia et al., 2019 [79] Tan et al., 2005 [80]
Consistency (plasticity)	Determines flow class (fluid, plastic, flowable) and ease of injection	w/b ratio, SCM replacement, superplasticiser (SP) dosage	Higher SCM replacement ↑ SP demand; adjusted water content can reduce SP use; yield stress/viscosity mapping supports design optimisation	Krishnamoorthy et al., 2002 [82] Sonebi et al., 2020 [83]
Injectability (penetrability)	Governs grout's ability to fill voids and fractures effectively	Rheological parameters (yield stress, viscosity), particle size, stability	Injectability depends on rheology and fracture aperture; poor penetrability compromises encapsulation	Bras & Henriques, 2011 [84]
Compressive and flexural strength	Determines load transfer and structural capacity	w/b ratio, curing time, SCM content	UCS ↑ with lower w/b; strength gains continue up to 28 days; bar bolts stiffer than cables due to bond uniformity	Aziz et al., 2017 [47]; Mirzaghorbanali et al., 2016 [44]; Benmokrane et al., 1995 [45]
Shear strength	Critical for resisting slip at grout–steel and grout–rock interfaces	Confining pressure, grout composition	Direct shear tests confirm shear resistance ↑ with confinement	Moosavi & Bawden, 2003 [43]
Toughness and resilience	Enhances performance under impact or dynamic loading	Use of rubber aggregates, nano-additives	Rubber ↓ strength but ↑ toughness; nanosilica densifies microstructure and ↓ permeability	Yuan et al., 2021 [85] Sonebi et al., 2015 [11]

* ↑: increase; ↓: decrease.

3.2.5. Microstructural Development and Rheological Behaviour

Research Cluster 2 focuses on two interconnected themes: microstructural development and rheological behaviour. Together they provide the critical link between the fresh, flowable state of cementitious grouts and the hardened matrices that ultimately ensure effective load transfer to reinforcement elements and surrounding rock. In fresh suspensions, rheology governs the ability of grouts to be injected into boreholes, whereas in the hardened state, the evolution of the microstructure through hydration and secondary reactions determines long-term stiffness, durability, and bond capacity. These two aspects are not independent; rather, rheology is a direct reflection of early microstructural changes that take place at the particle and gel scales.

The development of microstructure in cementitious grouts is primarily controlled by the hydration-driven formation of C–S–H gels, together with aluminate- and aluminosilicate-bearing hydrates, which progressively refine pore structures and interfacial transition zones. Early studies established that the hydration process follows the classic sequence of alite and belite dissolution, supersaturation of Ca^{2+} and OH^{-} ions, and precipitation of C–S–H and portlandite, with subsequent secondary reactions involving aluminates [52]. More recently, attention has shifted toward how SCMs and waste-derived binders alter these pathways. For instance, Guo et al. [57] reported that coal-based cementitious grouts form heterogeneous microstructures during early hydration, which strongly affect the cementation and bond with rock substrates. Similarly, Yuan et al. [9] examined grouts incorporating recycled municipal solid waste ash and found that reactive aluminosilicates promote secondary C–S–H and C–A–H formation, leading to more compact matrices with reduced porosity. Dai et al. [50] further highlighted the synergistic effects of blended SCMs, showing that the combined use of fly ash, slag, and silica fume accelerates gel formation and refines pore structures. Sha et al. [58] confirmed these trends in alkali-activated grouts, where rapid precipitation of C–A–S–H gels under alkaline conditions resulted in dense, durable matrices.

The rheological behaviour of fresh grouts is equally important, as it dictates injectability and encapsulation quality. Fresh grouts typically behave as yield-stress fluids that can be described by Bingham or Herschel–Bulkley models, with shear thinning and thixotropic characteristics arising from particle flocculation and early hydrate bridging [10]. In practical terms, this means that rheological parameters such as yield stress and plastic viscosity must be carefully controlled to ensure pumpability and uniform filling of boreholes. Zhao et al. [49] explored magnesium-based cementitious grouts and showed that tuning these parameters was essential for achieving homogeneous encapsulation. Dong et al. [48] confirmed that incorporating GGBS not only improved hardened-state performance but also stabilised rheological properties during placement, reducing segregation and bleeding risks. Beyond material composition, experimental investigations increasingly employ advanced rheometry to measure shear thinning behaviour and thixotropy, properties that strongly affect the workability of grouts in field applications [86].

Recent advances in granular micromechanics offer valuable mechanistic insight into the rheological behaviour of cementitious grouts. Studies on granular packing by Tong et al. [87] show that creep, ageing, and fluidity transitions are governed by packing fraction and the evolution of an internal state parameter that reflects the balance between stiffness and viscous relaxation. These findings are highly relevant to early-age grout behaviour, where particle–particle contacts, coordination number, and emergent force chains determine yield stress, thixotropy, and shear-rate sensitivity prior to significant hydration. The conceptual similarity between granular creep and grout viscosity evolution suggests that the fluidity and state-evolution formulations used for granular materials can help explain why cementitious grouts exhibit logarithmic creep, structural rebuilding, and abrupt transitions between solid-like and flowable states during mixing and pumping.

Particle shape is also a controlling factor that governs flow resistance and structural build-up. Tong et al. [88] demonstrated that angular or irregular particles increase interlocking and reduce system fluidity, whereas rounded particles reduce viscosity and promote deformation. These mechanisms align with observations in cementitious systems where angular clinker grains generate high static yield stress, while smoother supplementary cementitious materials improve workability and delay jamming. Incorporating these micromechanical concepts clarifies that grout rheology emerges not only from chemical hydration but also from the granular mechanics of particle shape, packing density, and internal structural evolution. Such constitutive insights strengthen the mechanistic interpretation of grout flow and thixotropy within the broader context of material composition and microstructure.

The interdependence of rheology and microstructure has become increasingly apparent in laboratory-scale studies. As hydration progresses, rheological parameters evolve rapidly due to particle aggregation and the onset of setting, while microstructural measurements using SEM, XRD, and mercury intrusion porosimetry (MIP) reveal corresponding changes in pore connectivity. Yuan et al. [9] observed that systems incorporating reactive waste ashes exhibited extended workable times with delayed stiffening, which correlated with the gradual nucleation of hydration products. In contrast, alkali-activated binders often display rheological instability in the first hours after mixing, driven by rapid dissolution of aluminosilicates, requiring careful optimisation of activator composition to ensure both workability and strength development [58].

Supplementary cementitious materials exert a strong influence on both rheology and microstructure. Nanosilica additions, for example, significantly increase yield stress and plastic viscosity because of their high surface area, while also accelerating hydration and refining pore structure, ultimately improving compressive strength [11]. Slag-rich systems, when combined with modern superplasticisers, typically display lower early viscosities and more stable rheological profiles, yet densify substantially at later ages through the development of C–A–S–H gels [63]. Recent work on limestone–calcined clay (LC3) systems illustrates another important point: calcined clays induce strong structural build-up due to their high surface reactivity, while carbonate-aluminate reactions generate hemicarbonate and monocarboaluminate phases that alter early microstructural development. These features produce rapid densification but also increase thixotropy, necessitating admixture strategies to balance workability and strength [89].

Temperature and shear history further complicate this interplay. Lootens et al. [90] showed that structural build-up during rest results from both reversible flocculation and irreversible hydrate bridging, with the latter portion not eliminated by shearing. This has practical implications: delays in pumping or long transit times may lead to partial stiffening that cannot be reversed, narrowing the injectability window. Moreover, temperature alters both rheological properties and hydration kinetics. Jiao et al. [12] demonstrated that viscosity and yield stress increase significantly at lower temperatures, while higher temperatures accelerate hydration and shorten the workability period, shifting the balance between reversible and irreversible structuration.

The microstructure of the grout–rock or grout–steel interface is particularly critical for reinforcement performance. Constantinides, Ulm [13] used statistical nanoindentation to reveal gradients in stiffness and porosity across the ITZ, while Hou et al. [14] showed that interfacial densification correlates with improved shear transfer and reduced slip. Weak or porous ITZs can act as preferential planes for debonding under load, whereas a dense, well-bonded ITZ supports efficient stress transfer and durability. Admixtures that suppress bleeding and promote uniform early hydration are therefore essential for optimising microstructural development at these interfaces.

4. Summary of Review Findings

4.1. Mechanistic Insights from Material Composition, Rheology, and Microstructure

Table 6 synthesises the key findings of this systematic review on the characteristics of cementitious grouts used in ground support systems. Citation analysis indicates that

Construction and Building Materials dominates the field with 28 publications and 771 citations, followed by the Journal of Building Engineering and Case Studies in Construction Materials with 8 and 7 publications, respectively. Together, these three journals account for nearly half of the outputs and the majority of citations, highlighting Elsevier's strong influence on this research domain.

Table 6. Summary of the main findings.

Top Contributing Journals	Co-Authorship Analysis: Leading Authors	Co-Authorship Analysis: Leading Institutions	Research Hot Spots	Frequency of Keywords Analysis
- Construction and Building Materials - Journal of Building Engineering - Case Studies in Construction Materials	- Celik, Fatih - Canakci, Hanifi - Zhang, Qingsong	- Shandong University - Gaziantep University - University of Science and Technology Beijing	- Rheological behaviour, mechanical properties, reinforcement, supplementary cementitious materials - Workability, chemical reactions, microstructure	- Rheological behaviour - Mechanical properties - Reinforcement - Workability - Chemical reactions - Microstructure - Supplementary cementitious materials

Institutional analysis identified Shandong University as the most productive contributor with five publications and 170 citations, while Gaziantep University leads in impact with 200 citations across three studies. Other highly influential institutions include Harbin Institute of Technology (160 citations) and the University of Western Australia (153 citations). Notably, Chinese universities account for seven of the top ten institutions, underscoring China's dominant role, complemented by impactful contributions from Turkey and Australia.

Co-authorship analysis revealed 41 core authors with at least two publications, out of a total of 449 contributors. Among them, Celik Fatih emerged as the most productive with five publications and 189 citations, while Canakci Hanifi achieved the highest citation impact with 200 citations from three publications. Strong collaborative ties were identified within several clusters, such as the partnership of Song, Zhu, Wan, Huo, and Pu on alkali-activated materials, which collectively achieved over 130 citations, and the work of Zhang and Zhang on alternative grout systems, whose two papers between 2022 and 2023 accumulated 39 citations.

The keyword co-occurrence network refined through thesaurus mapping produced 28 high-impact terms, ultimately organised into two clusters connected by 19 links. Cluster 1 encompassed reinforcement, mechanical properties, supplementary cementitious materials, and rheological behaviour, while Cluster 2 included workability, chemical reactions, and microstructure. This division mirrors the dual focus of the literature: advancing material science innovations to optimise fresh and hardened properties and simultaneously deepening mechanistic understanding of grout–rock interactions and encapsulation chemistry.

4.2. Field-Scale Behaviour and Underground Boundary Conditions

Field observations from tunnelling and mechanised excavation indicate that grout performance cannot be fully understood without considering the stress paths and boundary conditions imposed during excavation. In underground settings, the grout column is subjected to evolving confinement, cyclic cutterhead vibrations, penetration-induced stress redistribution, and pressure gradients associated with annular gap closure. These factors influence bleeding, early-age stiffness gain, and load transfer along the reinforcement.

Recent Tunnel Boring Machine (TBM) studies show that thrust force, penetration rate, and torque respond sensitively to transitions in rock mass quality, discontinuity spacing, and groundwater inflow, creating complex loading histories that grouts must withstand before full hydration and microstructural stabilisation. Advanced data-driven analyses from mechanised tunnelling further reinforce this link between excavation dynamics and grout behaviour. Fu et al. [91] demonstrated that TBM thrust signals exhibit strong non-stationarity and multimodal behaviour controlled by lithological variability and cutter–rock interaction patterns. These fluctuations generate short-duration load peaks and unloading cycles at the excavation boundary, which can affect the consolidation, rheological evolution, and bond mobilisation of early-age cementitious grouts. By integrating these insights, it becomes clear that grout design cannot rely solely on laboratory rheology or compressive strength; instead, field-scale excavation dynamics must be accounted for when evaluating mixture stability, setting kinetics, and long-term load-transfer efficiency in tunnelling environments.

4.3. Time-Dependent Mechanical Behaviour and Long-Term Degradation

Long-term performance of cementitious grouts is governed by a set of coupled time-dependent mechanisms that extend beyond initial strength and rheological measurements. Sustained loading leads to primary and secondary creep through viscous flow in the C–S–H gel and progressive rearrangement of hydrates, while chemically aggressive underground conditions promote degradation by carbonation, sulphate attack, acidic mine water, or chloride ingress. Relaxation at the grout–tendon interface is also common, driven by shrinkage-induced microcracking, cyclic excavation stresses, and gradual softening of the grout–steel or grout–GFRP bond. Collectively, these mechanisms can diminish long-term load-transfer efficiency, particularly in tunnels and mining environments where stress paths, vibration levels, and groundwater pressures vary over time.

The evolution of these processes can be conceptualised as a dual-phase trajectory similar to the degradation–recovery patterns described by Zhang et al. [92]. In the short term, phenomena such as early-age creep, moisture redistribution, and chemical softening may lead to temporary reductions in stiffness and bond capacity. Over longer periods, however, secondary hydration, pozzolanic reactions, and slow densification of the microstructure can result in partial mechanical recovery or stabilisation. Viewing grout behaviour through this dual-phase lens emphasises the limitations of short-duration laboratory tests and underscores the need for predictive models that incorporate time-dependent degradation and field-calibrated performance data under realistic underground boundary conditions.

4.4. Unresolved Issues and Research Needs

Despite substantial advances in understanding cementitious-grout behaviour, several issues remain unresolved. First, current rheological and mechanical models only partially capture the interplay between hydration kinetics, particle-scale micromechanics, and evolving packing structure, leaving gaps in predictive capability under realistic field conditions. Second, most studies evaluate grout behaviour under controlled laboratory environments, and there is limited validation against the complex stress paths, vibration cycles, and groundwater pressures encountered in underground construction and mechanised tunnelling. Third, sustainability-focused mix designs incorporating SCMs or waste materials require deeper investigation of long-term durability and compatibility with reinforcement performance. These gaps highlight the need for more integrative, field-calibrated approaches linking compositional design, microstructure development, and in situ performance.

5. Conclusions and Future Research Directions

This review combined PRISMA-guided bibliometric mapping with a mechanistic synthesis to provide an integrated understanding of cementitious grouts used in ground-support systems. The bibliometric analysis showed that global research activity is concentrated around themes of reinforcement performance, rheology, supplementary cementitious materials, and microstructural characterisation, supported by a collaboration network led by a small number of influential institutions. The technical synthesis consolidated five key domains—reinforcement mechanisms, grout composition, chemical and pozzolanic reactions, fresh and hardened-state behaviour, and microstructural development—highlighting how advances in material design and analytical techniques have reshaped the understanding of grout–rock–bolt interactions. Across these domains, supplementary cementitious materials and waste-derived binders continue to play a central role in improving mechanical performance while reducing environmental impact. Collectively, the findings underline that cementitious grouts operate as engineered composites whose performance is governed by the interplay between composition, rheology, microstructure, and in situ boundary conditions. Although substantial progress has been made in understanding cementitious-grout behaviour, several broader research needs remain. Future studies should prioritise the development of constitutive models that couple hydration reactions with particle-scale mechanics to better capture early-age deformation and flow. There is also a need for more field-calibrated data that considers the influence of excavation-induced loading, groundwater conditions, and long-term degradation processes on grout stability. Additionally, the growing shift toward low-carbon materials highlights the importance of linking sustainable mix design with durability performance and life-cycle assessment. Advancing these areas will support the design of next-generation grouts capable of meeting long-term safety, durability, and environmental requirements.

Author Contributions: Conceptualisation, A.E., H.N., P.B., K.M., P.C., B.J.S., S.E., N.A. and A.M.; methodology, A.E., H.N., P.B., K.M., P.C., B.J.S., S.E. and A.M.; software, A.E., B.J.S. and S.E.; validation, A.E., H.N., P.B., P.C., B.J.S., S.E. and A.M.; formal analysis, A.E., H.N., P.B., K.M., P.C., B.J.S., S.E., N.A. and A.M.; investigation, A.E.; resources, A.E., H.N., P.B., K.M., P.C., B.J.S., S.E. and A.M.; data curation, A.E.; writing—original draft preparation, A.E.; writing—review and editing, A.E., H.N., P.B., K.M., P.C., B.J.S., S.E., N.A. and A.M.; visualisation, A.E.; supervision, P.B., K.M. and A.M.; project administration, P.B. and A.M.; funding acquisition, P.B. and A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been funded by the Australian Department of Education through a Regional Research Collaboration (RRC) grant. This funding has allowed the establishment of the University of Southern Queensland-led SIMPLE Hub where this research has been conducted.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Peter Craig was employed by the company Jennmar Australia. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FGRB	Fully grouted rock bolt
FGCB	Fully grouted cable bolt
OPC	Ordinary Portland cement
SCM	Supplementary cementitious material
GGBS	Ground granulated blast-furnace slag

SEM	Scanning electron microscopy
XRD	X-ray diffraction
ITZ	Interfacial transition zone
W/G	Water-to-grout
UCS	Unconfined compressive strength
GO	Graphene oxide
FA	Fly ash
RHA	Rice husk ash
SS	Steel slag
nS	nanosilica
CFA	Coal fly ash
CSA	Calcium sulfoaluminate
SVM	Support vector machines
FRP	Fibre-reinforced polymer
C-S-H	Calcium silicate hydrate
C-(A)-S-H	Calcium (alumino)silicate hydrate
w/b	Water-to-binder
SP	Superplasticiser
MIP	Mercury intrusion porosimetry
LCA	Life-cycle assessment
TBM	Tunnel boring machine
GFRP	Glass fibre reinforced polymer

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